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Turbomachinery Technology for High-Speed Civil Flight

Neal T. Saunders and Arthur J. Glassman
Lewis Research Center
Cleveland, Ohio

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TURBOMACHINERY TECHNOLOGY FOR HIGH-SPEED CIVIL FLIGHT

Neal T. Saunders
and
Arthur J. Glassman

ABSTRACT

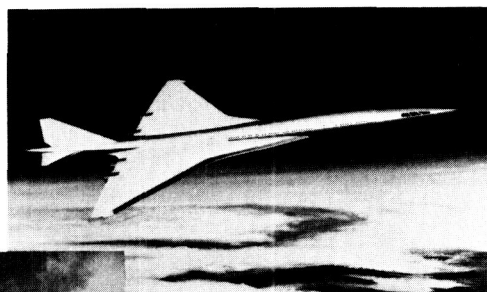
This presentation highlights some of the recent contributions and future directions of NASA Lewis Research Center's research and technology efforts applicable to turbomachinery for high-speed flight. For a high-speed civil transport application, the potential benefits and cycle requirements for advanced variable cycle engines and the supersonic throughflow fan engine are presented. The supersonic throughflow fan technology program is discussed. Technology efforts in the basic discipline areas addressing the severe operating conditions associated with high-speed flight turbomachinery are reviewed. Included are examples of work in internal fluid mechanics, high-temperature materials, structural analysis, instrumentation and controls.

INTRODUCTION

Future Emphasis Shifting to High-Speed Flight

Two years ago, the aeronautics community commemorated the 50th anniversary of the first successful operation of a turbojet engine. This remarkable feat by Sir Frank Whittle represents the birth of the turbine engine industry, which has greatly refined and improved Whittle's invention into the splendid engines that are flying today. NASA, as did its predecessor NACA, has assisted industry in the creation and development of advanced technologies for each new generation of engines. NASA's research efforts of the 1970's and early 1980's were directed at the high-bypass turbofan engines that are powering today's fleet of commercial transports. Some of our more recent efforts have been aimed toward the development of advanced turboprop engines which may lead to the introduction of a new generation of transports in the mid-1990's. Aeropropulsion research efforts at NASA Lewis Research Center are now shifting toward advanced propulsion systems for high-speed flight, including advanced engines that might power high-speed transports in the 21st century.

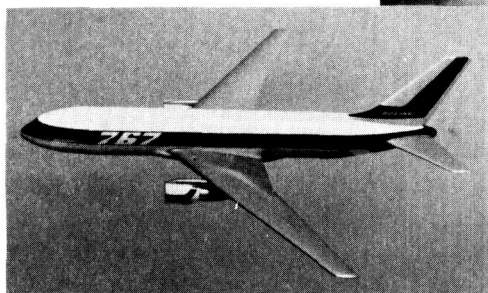
FUTURE EMPHASIS ON PROPULSION FOR HIGH-SPEED FLIGHT



2000's



1990's



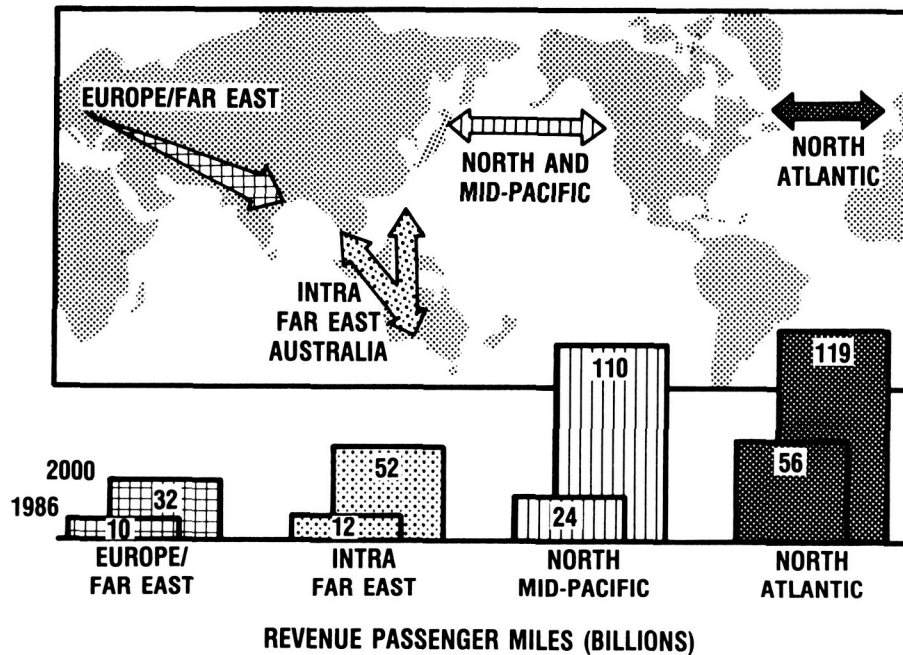
1980's

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Why High-Speed Transport?

This international passenger traffic projection indicates a significant growth in revenue passenger miles by the year 2000—a 100 percent increase over the North Atlantic and a 300 to 400 percent increase over the North/Mid-Pacific. Such a growth can be accommodated by increasing number of aircraft, size and/or speed. Given the number of aircraft in the skies today and the already large size of the wide-body aircraft, the most likely solution to increased productivity is increased speed. High speed provides the additional advantage of reduced travel time and traveler fatigue on the long overseas flights. Today's advanced technology provides a potential for success that was not available when the previous supersonic cruise research program was being conducted during 1971 to 1981.

INTERNATIONAL PASSENGER TRAFFIC PROJECTION



- **HIGH SPEED PROVIDES**
 - INCREASED PRODUCTIVITY
 - REDUCED TRAVEL TIME/TRAVELER FATIGUE
- **ADVANCED TECHNOLOGY PROVIDES POTENTIAL FOR SUCCESS**

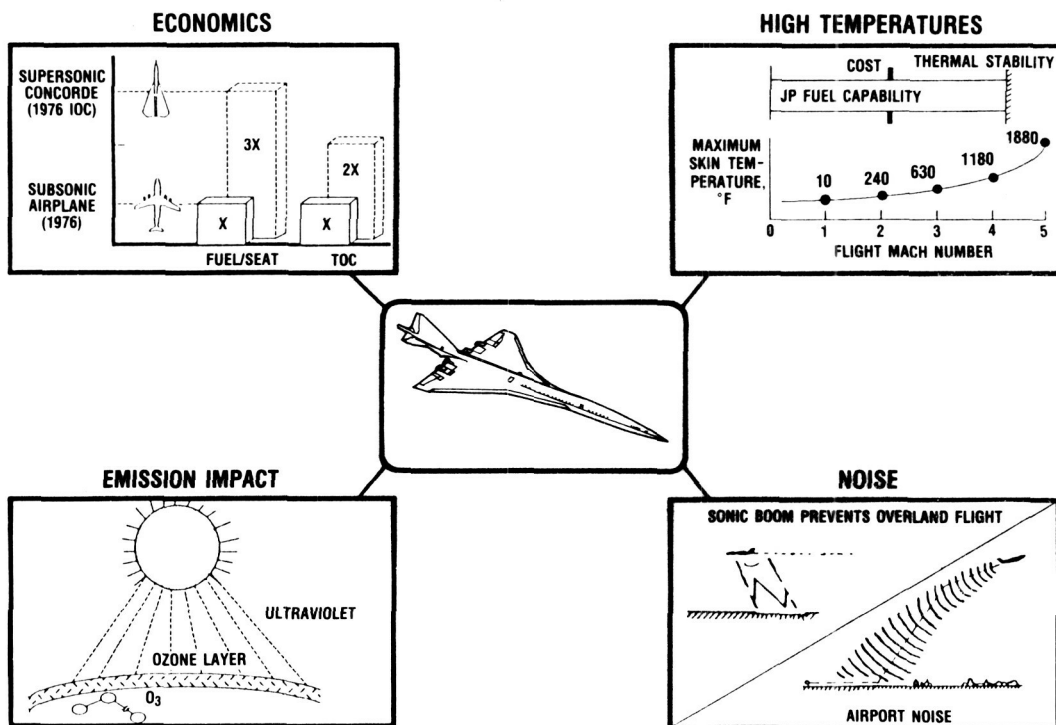
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Challenges to High-Speed Transports

Although the Concorde ushered in the supersonic transport era, it has not been a commercial success for a variety of reasons. Its poor fuel consumption is largely responsible for its uncompetitive economics. Large airframe and propulsive efficiency improvements will be required to alter this situation. In our quest for greater productivity through increased speed, we are confronted with an ever increasing technical challenge arising from high ram temperature levels. In addition to airframe skin temperature problems, the inability of readily-available low-cost fuels to provide adequate thermal stability seriously impedes the pursuit of higher speeds. While both sonic boom and airport noise levels are currently excessive, only the airport noise problem is of primary concern to the propulsion industry. Another potential environmental issue is the depletion of atmospheric ozone via jet engine exhaust-gas emissions.

This presentation will address some of the advanced engines that appear to have the potential to provide the needed improvements in propulsive efficiency. Included are the effects of noise and emissions constraints on performance. One particular concept, the supersonic throughflow fan engine, is being explored in a NASA Lewis technology program. Also discussed are some of the discipline technology efforts that support the needs of turbomachinery for high-speed flight.

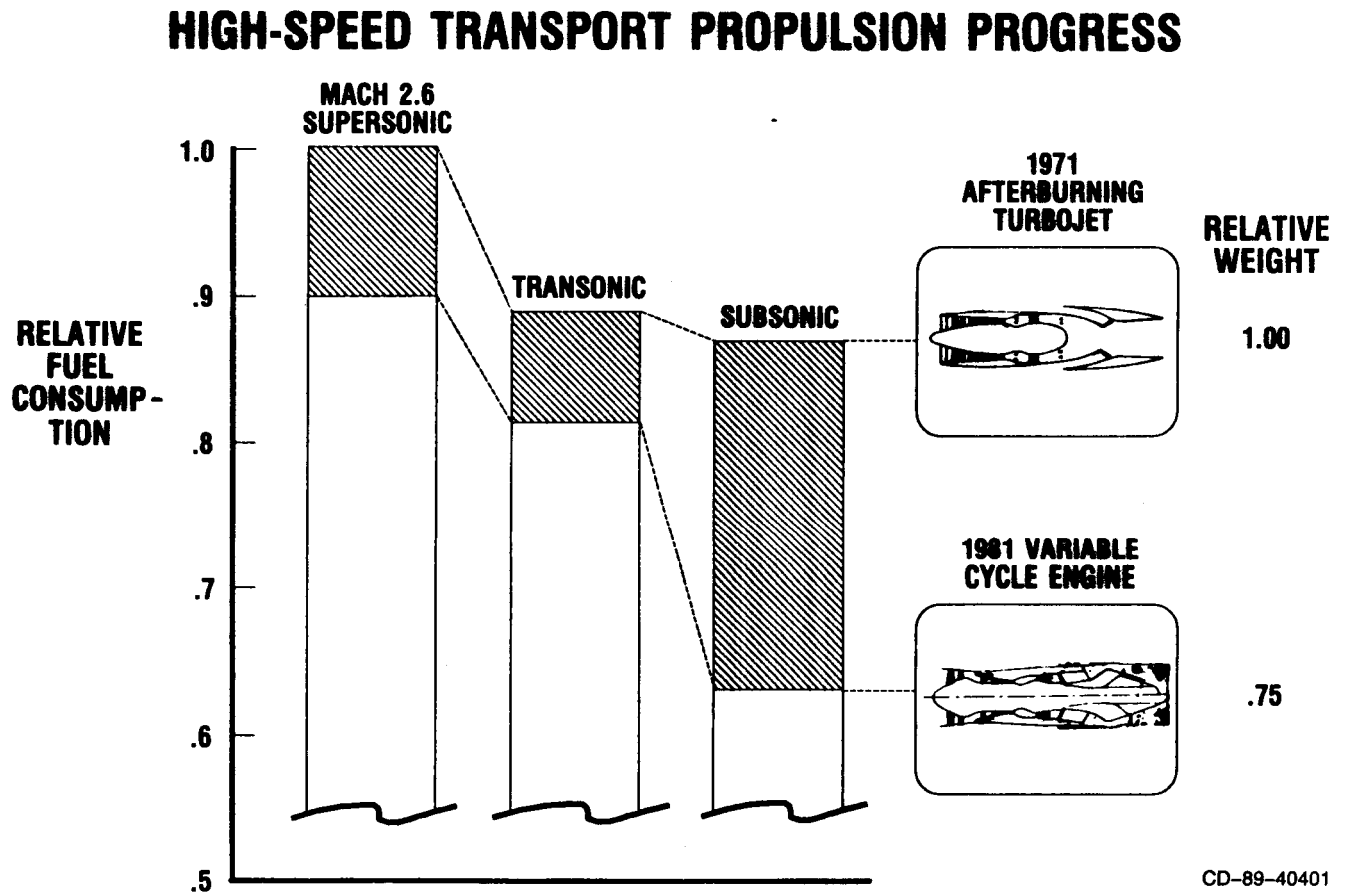
CHALLENGES TO HIGH-SPEED TRANSPORTS



PROPULSION SYSTEMS OPPORTUNITIES

High-Speed Transport Propulsion Progress

Considerable progress was achieved during the 1970's in the NASA-sponsored variable-cycle engine (VCE) program. Compared to a 1971 afterburning turbojet, the 1981 VCE's consumed 10 percent less fuel at supersonic and transonic conditions, and 25 percent less at subsonic speeds--reflecting the cycle-changing feature of VCE's. A simultaneous 25 percent reduction in engine weight occurred. Nevertheless, these gains are insufficient by themselves to enable competition with subsonic aircraft. The subsonic efficiency of the 1981 VCE engines, for example, is still only one half that of today's high bypass-ratio turbofans.

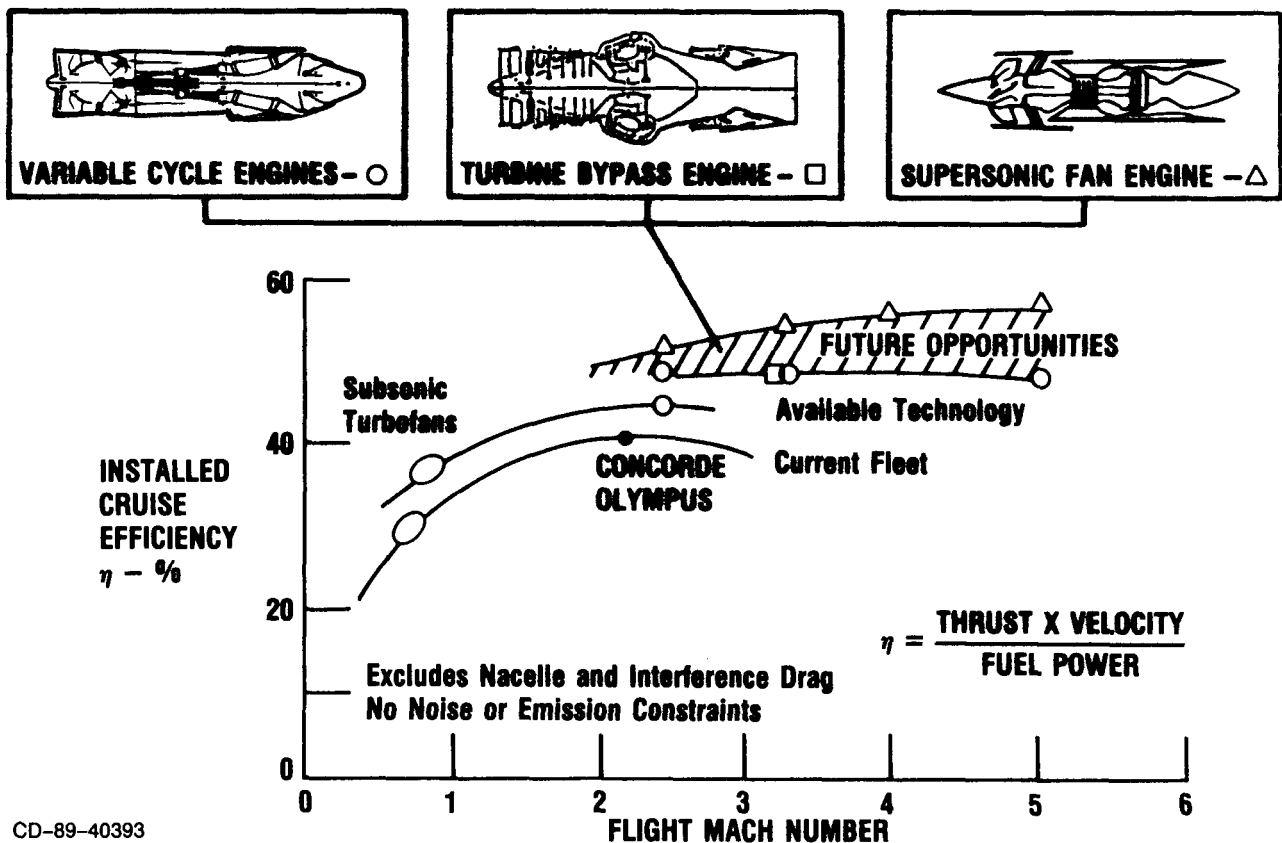


Future High-Speed Propulsion Performance Potential

The primary cause of the Concorde's high fuel consumption is the supersonic speed lift-to-drag ratio (L/D) which is on the order of one-half that of subsonic transports. This is only partially offset by the trend toward increasing overall engine efficiency with flight speed. Installed cruise efficiency shown here includes inlet and nozzle losses, but not nacelle drag, and represents design point values. The middle curve indicates that significant improvement is possible with today's available technology for both subsonic and supersonic regimes.

The top band projects future opportunities based principally on NASA cycle analyses. Several alternative cycle concepts are represented, including very advanced VCE and turbine bypass engines (lower boundary), and an innovative concept known as the supersonic throughflow turbofan (upper boundary). Gains of 35 percent or more over Concorde's Olympus engine are possible. Using a simple criterion such as design point efficiency, however, is insufficient to properly convey overall impact. For example, this plot shows a relatively modest gain between current technology VCE's and advanced VCE's (lower line of top band). Not shown, but also important, are even larger gains in climb efficiency and weight for advanced VCE's.

FUTURE HIGH-SPEED PROPULSION PERFORMANCE POTENTIAL



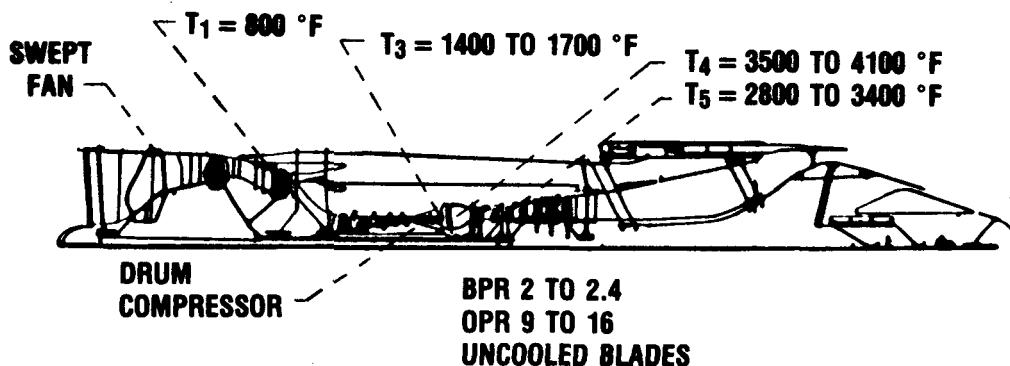
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Variable-Cycle Engine Goal

One obvious contender for a future high-speed transport is an advanced variable-cycle engine. This approach builds on the previous VCE philosophy of incorporating enough variable geometry features to yield improved performance over a wide range of flight speeds and power settings. Displayed here is an example of a goal VCE, representing what payoffs would accrue if revolutionary advances in materials and structures technology are achieved. It assumes essentially uncooled stoichiometric engine materials coupled to advanced aerodynamics and structural design technologies. This implies extensive use of nonmetallic and intermetallic materials.

Two levels of technology are quoted here: (1) the full near-stoichiometric goal level is denoted by the right-hand values and (2) a 600 °F cooler level is denoted by the left-hand values. One-third of the potential 32-percent fuel reduction is due to a 45-percent engine weight reduction relative to a hypothetical 1984 technology-readiness baseline engine. A key point to note here are the high temperatures in the compressor and the turbine. This is representative of what is required to maximize performance, and indicates the need for high temperature technology efforts in the discipline areas.

VARIABLE-CYCLE ENGINE GOAL POTENTIAL MACH 3 CRUISE CONDITIONS



**BENEFITS (MATERIALS AND AERO): 290 PAX 5000 nmi TRANSPORT
RELATIVE TO CURRENT TECHNOLOGY AT \$.60/gal.**

| | |
|-------------|------------------|
| FUEL | 27 TO 32% |
| DOC | 13 TO 15% |

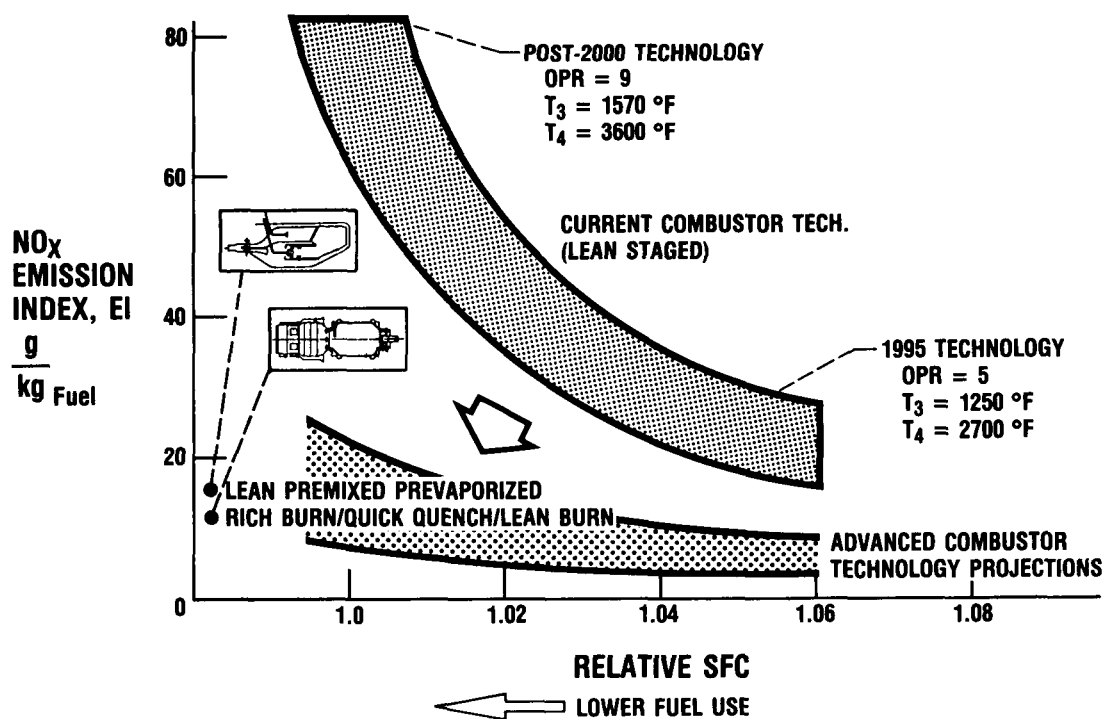
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Effect of NO_x Emissions Constraints

The higher temperature and pressure operating conditions required for improved engine performance lead to excessive NO_x emissions. With current staged-combustor technology, operation at less severe conditions with acceptable penalties in fuel consumption and engine size will still not reduce the NO_x emission index to the goal value of five. To achieve the desired reduction in NO_x will require advanced combustor technology such as a lean premixed pre-vaporized concept or a rich burn/quick quench/lean burn concept.

EFFECT OF CYCLE PARAMETERS ON NO_x EMISSIONS AND FUEL CONSUMPTION

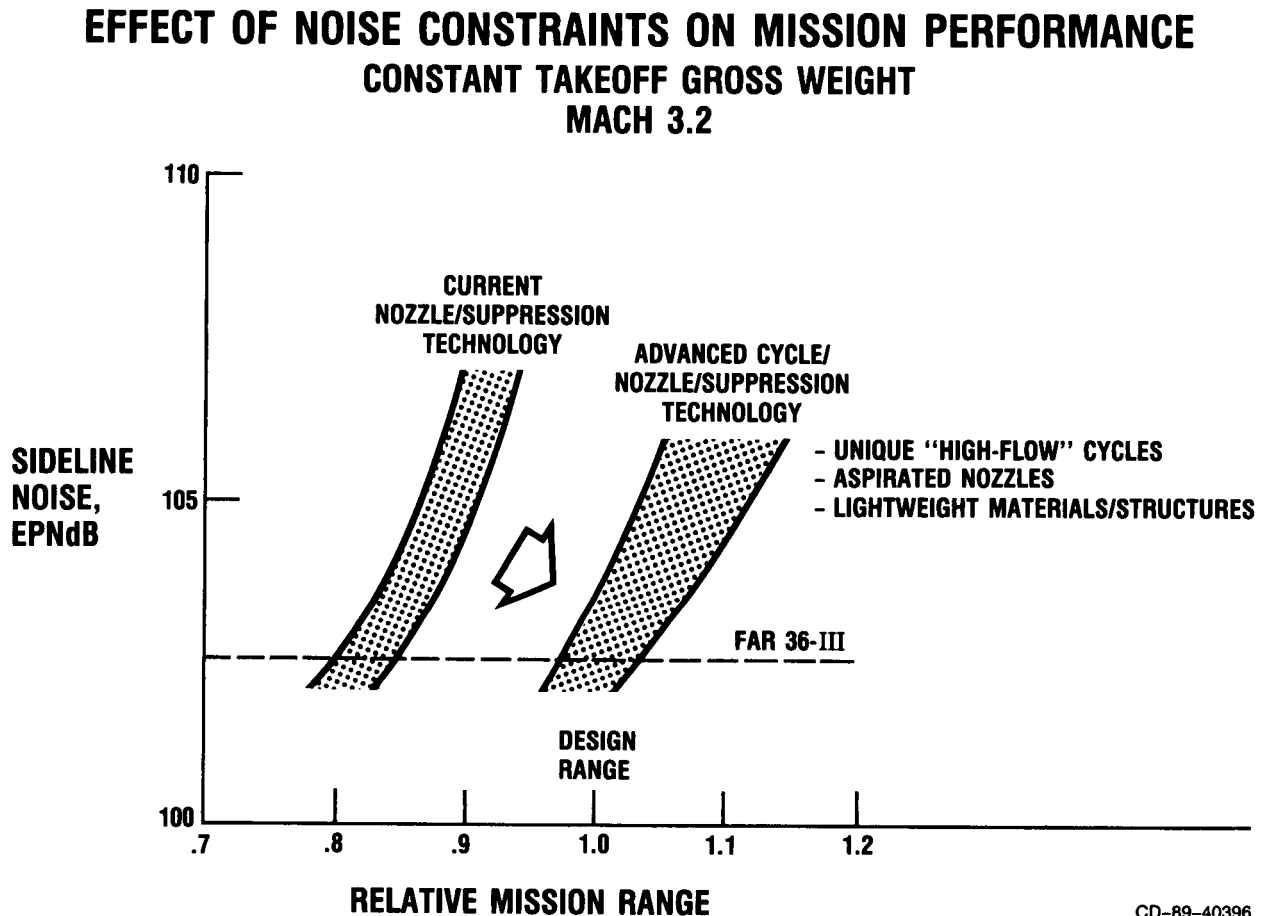
Mach 2.6



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Effect of Noise Constraints

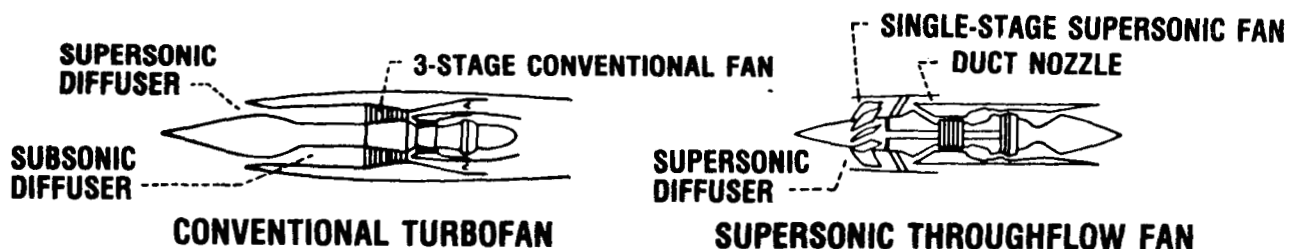
With current nozzle and suppression technologies, the stringent noise limits of FAR 36 Stage III can not be met with the advanced engine conditions for a high-speed civil transport having a transpacific range. Only an aircraft with a significantly oversized engine can meet the sideline noise limit of 102 to 103 EPNdB, but this aircraft will suffer a significant range penalty under conditions of constant takeoff gross weight. Advanced technologies such as unique engine cycles having a high-flow capability at takeoff and unique aspirated nozzles are being explored. The use of lightweight materials and structures can ease the problem somewhat through reduced aircraft and engine weight and, therefore, reduced thrust requirement.



Supersonic Throughflow Fan Engine

One innovative concept being pursued at NASA Lewis for high speed civil transport propulsion is the supersonic throughflow fan. Instead of using a long and heavy inlet system to efficiently decelerate the inlet airflow to the subsonic speeds required by conventional turbomachinery, the supersonic fan efficiently processes air at supersonic throughflow velocities. The advantages include much lower inlet-system weight, lighter fan (less stages required for a given pressure ratio), less boundary-layer bleed drag, better inlet flow stagnation pressure recovery, and better matching of bypass ratio variations to flight speed.

SUPERSONIC THROUGHFLOW FAN ENGINE



SUPERSONIC THROUGHFLOW FAN ENGINE

FEATURES:

- SHORT ALL-SUPERSONIC INLET
- SINGLE-STAGE SUPERSONIC FAN
- BYPASS RATIO DECREASES WITH INCREASING M_0

POTENTIAL BENEFITS (Mach 3 Transport):

- 25 PERCENT REDUCTION IN PROPULSION SYSTEM WEIGHT
- 20 PERCENT FUEL SAVINGS

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Supersonic Throughflow Fan Technology Needs

The supersonic throughflow fan engine has shown a potential to provide more efficient long-range supersonic flight. Unfortunately, the data base for components of this type is practically nonexistent. Therefore, in order to furnish the required information for assessing this type of fan, NASA Lewis has begun a program to design, analyze, build, and test a fan stage that is capable of operating with supersonic axial velocities from inlet to exit. The objectives are to demonstrate the feasibility and potential of supersonic throughflow fans, to gain a fundamental understanding of the flow physics associated with such systems, and to develop an experimental data base for design and analysis code validation. The ability to achieve and maintain supersonic flow through the complete stage will be explored first, followed by subsonic performance and transition behavior.

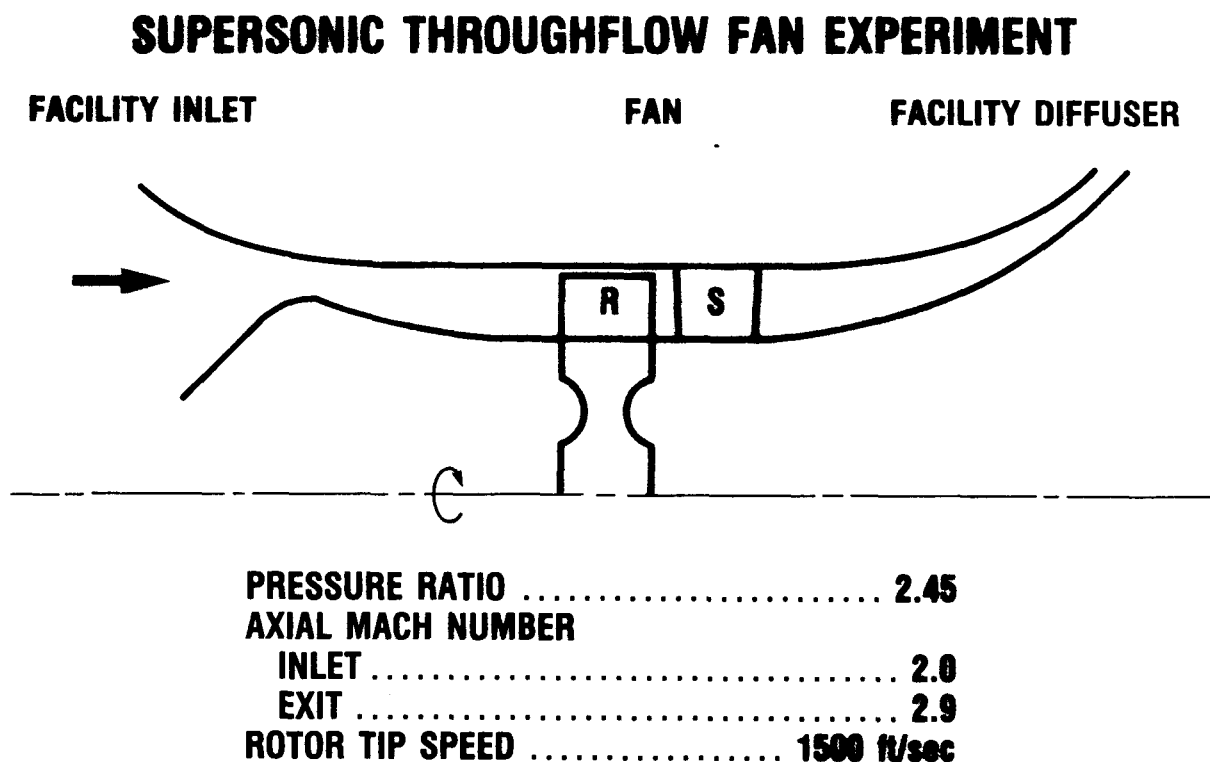
SUPERSONIC THROUGHFLOW TECHNOLOGY NEEDS

- **OBTAIN EXPERIMENTAL DATA FOR FLOW PHYSICS MODELING, CODE VERIFICATION AND PERFORMANCE DEMONSTRATION**
 - **SUPERSONIC PERFORMANCE**
 - **SUBSONIC PERFORMANCE**
 - **TRANSITION**
 - **CHOKE, STALL, AND UNSTART EFFECTS**
 - **DISTORTION TOLERANCE**
 - **FLUTTER AND FORCED RESPONSE EFFECTS**
- **EXTEND AND VALIDATE CODES**
 - **SUPERSONIC THROUGHFLOWS**
 - **ENDWALL BOUNDARY LAYER FLOWS**
 - **BLADE ROW INTERACTIONS**
 - **UNSTEADY FLOWS**
 - **DESIGN AND OFF-DESIGN PERFORMANCE PREDICTIONS**

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Supersonic Throughflow Fan Experiment

This figure depicts the experiment currently being performed at NASA Lewis. It consists of a supersonic throughflow fan, the facility inlet needed to accelerate the flow to supersonic velocities at the fan face, and the diffuser needed downstream to decelerate the supersonic flow leaving the fan to subsonic conditions downstream. The design Mach number at the fan face is 2.0 and the exit Mach number is 2.9. The fan was designed with a constant annulus area. The design pressure ratio (2:45) and tip speed (1500 ft/sec) were selected to be representative of those required of a turbofan engine fan operating at supersonic cruise conditions.

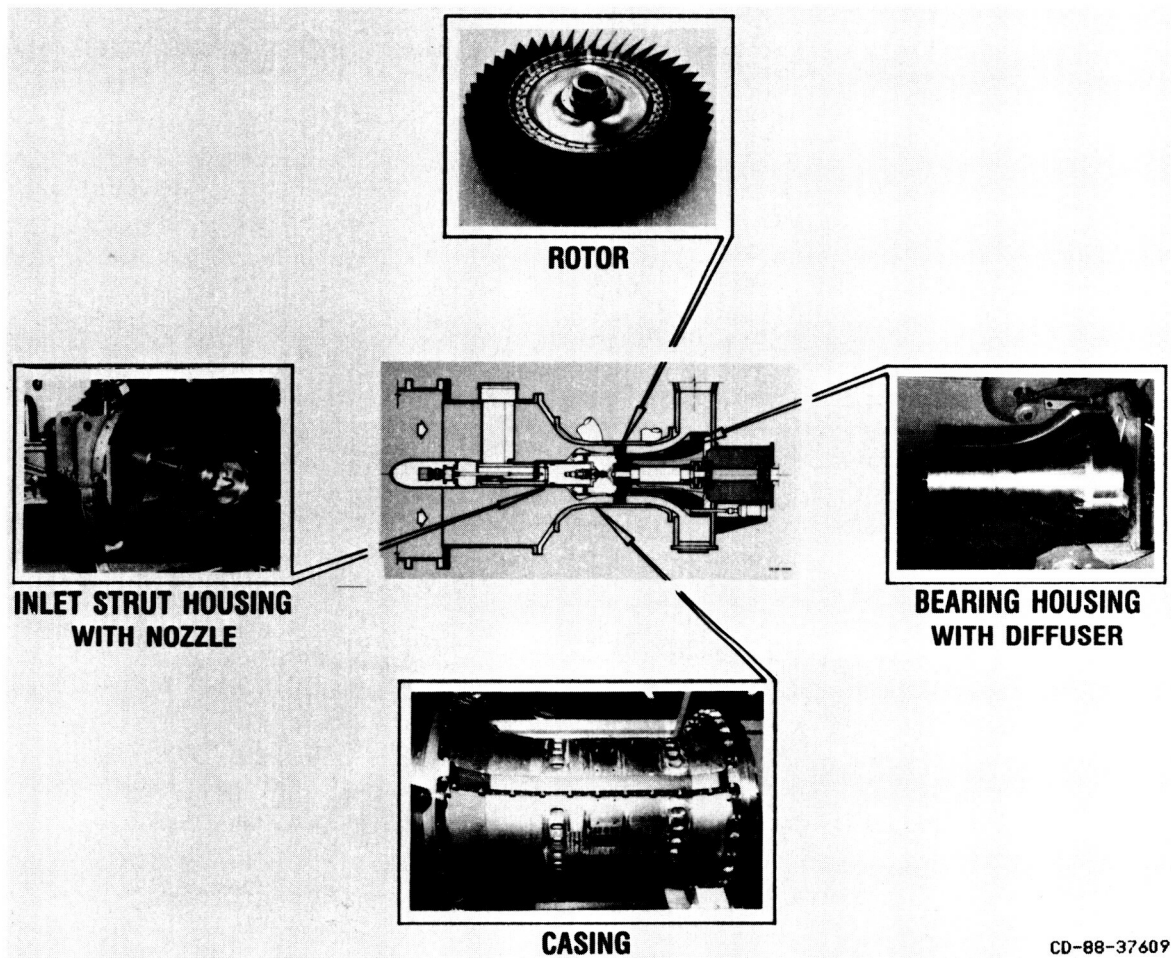


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Supersonic Throughflow Fan Test Package

This figure presents a sketch of the supersonic throughflow fan test package along with photographs of some of the fabricated parts. The variable-inlet nozzle and the variable downstream diffuser will be used to provide control over the fan-face Mach number and the diffusion of the supersonic fan exit velocities to subsonic conditions entering the exhaust system. Boundary layer bleed capability is provided at the inlet to the fan and the diffuser. Rotor tests are scheduled to be initiated near the end of 1989 with full stage tests to be conducted early in 1990. Laser anemometry tests for code validation will be conducted after the base performance has been established.

SUPERSONIC THROUGHFLOW FAN TEST PACKAGE



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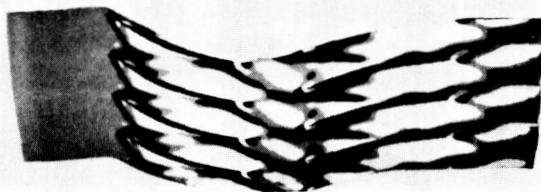
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DISCIPLINE TECHNOLOGIES

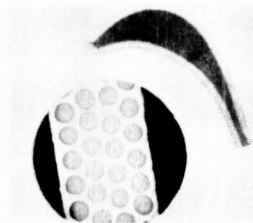
Technologies for High-Speed Propulsion Turbomachinery

New technologies required for high-speed transport propulsion start with the engine itself. A high-speed transport, for example, will require a novel propulsion system such as a variable cycle engine, a supersonic throughflow fan engine, or one of several other unique engines being studied. These engines, to achieve acceptable performance, will expose the turbomachinery to higher temperatures and pressures than previously encountered. Technology efforts in the basic discipline areas are being directed, in addition to supersonic throughflow, at turbomachinery operation in the severe temperature and pressure environments. Included herein are examples of work in internal fluid mechanics, high-temperature materials, structural analysis, instrumentation and controls.

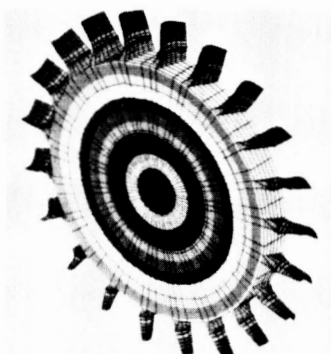
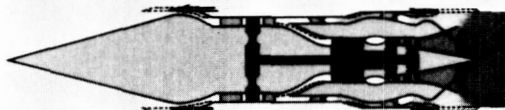
DISCIPLINE TECHNOLOGIES FOR HIGH-SPEED PROPULSION TURBOMACHINERY



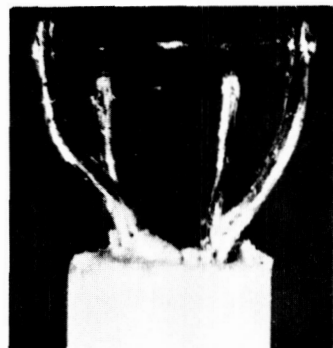
INTERNAL FLUID MECHANICS



HIGH-TEMPERATURE MATERIALS



STRUCTURAL ANALYSIS

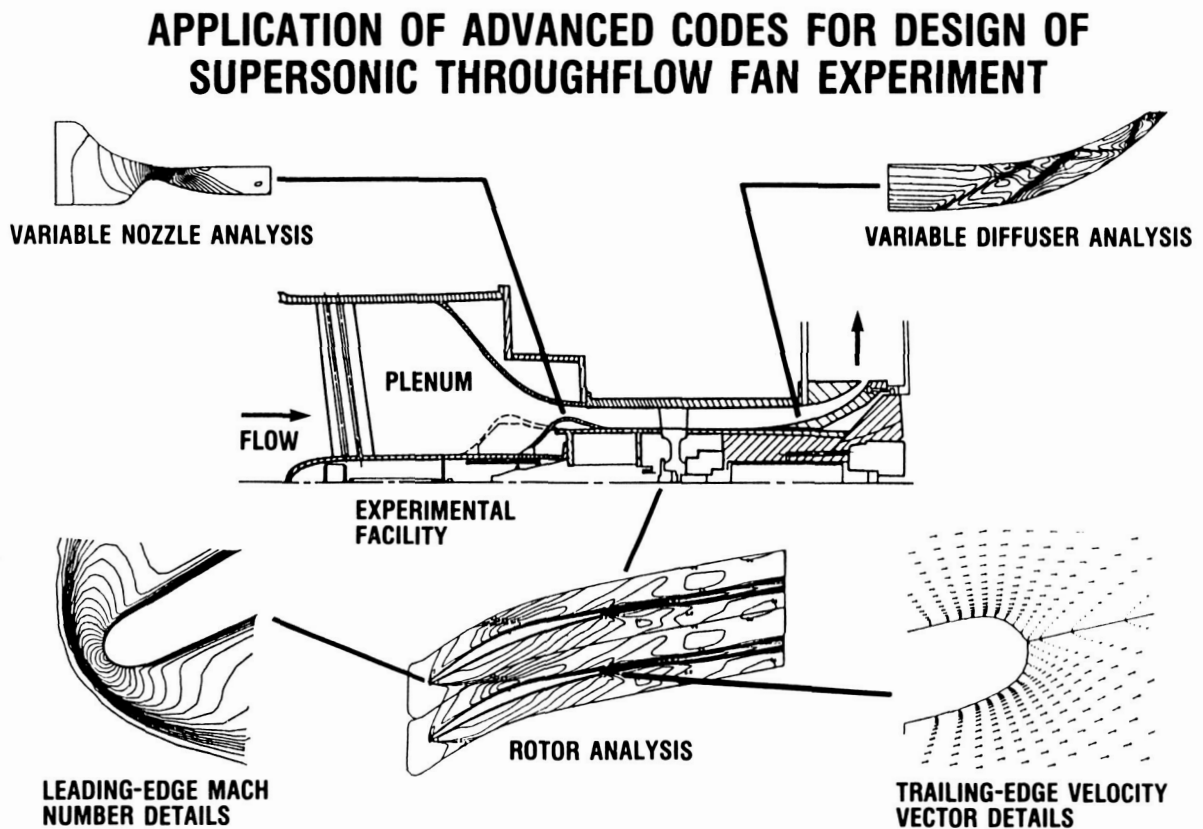


INSTRUMENTATION/CONTROLS

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Advanced Codes for Design of Supersonic Throughflow Fan Experiment

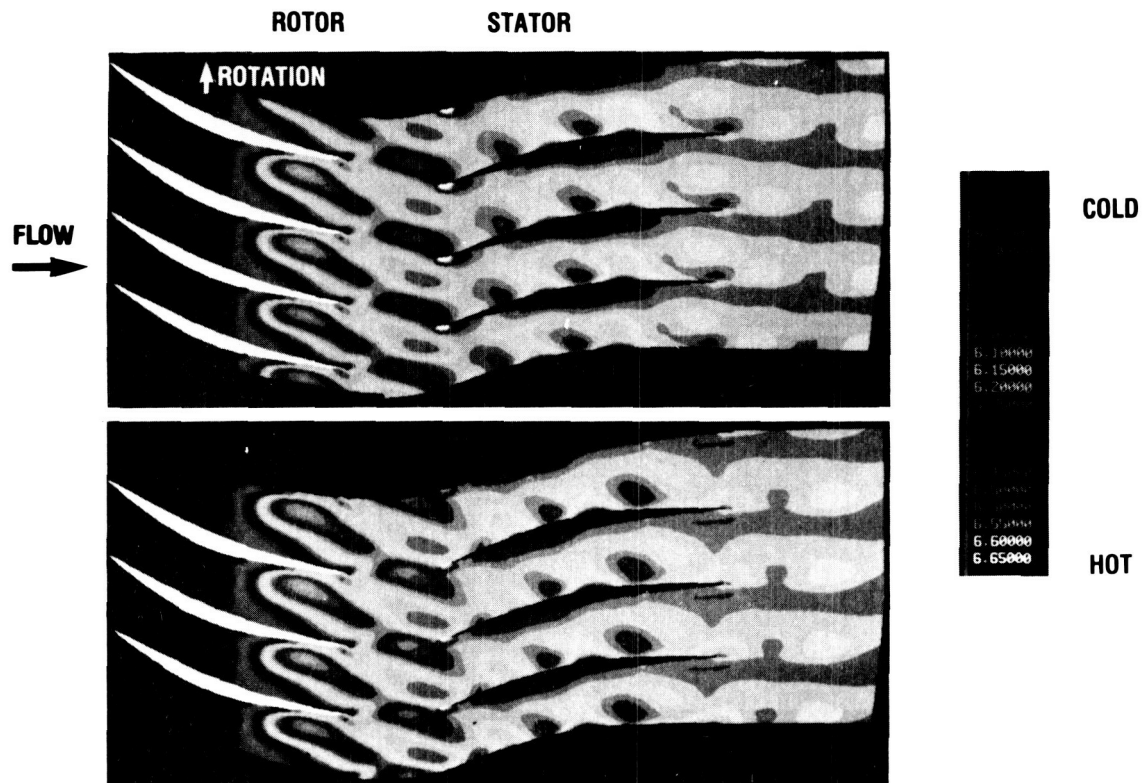
Since the data base for supersonic throughflow fans is practically nonexistent, design of any experiment to study feasibility of this concept must rely heavily upon advanced computational tools to enhance the possibility of success. All components were analyzed with two different codes in order to give increased confidence in the computed results. Computer codes, both inviscid and viscous, that have been developed for design and analysis of transonic turbomachines were modified to allow calculations of blade rows with supersonic inlet Mach numbers. An inviscid/viscous code and a parabolized viscous code were used to design and analyze the variable nozzle and variable diffuser necessary for the experiment. Off-design analysis of the various components of the experiment indicated that all components would operate as expected over the flow and speed range of the experiment. The figure shows the results obtained for the inlet variable nozzle which sets up the inlet flowfield, the fan rotor, and the variable diffuser which decelerates the flow toward the collector inlet.



Supersonic Throughflow Fan Rotor-Stator Interaction

A three-dimensional unsteady Euler analysis for the supersonic through-flow fan showed the rotor-stator interactions which occur at design operating conditions. One of the interactions under study is the formation of hot spots at the leading edge of the stator. This figure shows the stagnation enthalpy, and thus temperature, for two different positions of the rotor blades relative to the stators. The interactive wave patterns within and exiting the rotor result in a time-dependent flowfield entering the stator. The cyclic nature of the local temperature is apparent from the difference in the magnitudes of the local white (highest temperature) regions. The hot spots are believed to be caused by the motion of the shock wave emanating from the stator pressure surface. Further analysis is needed to fully understand this phenomenon.

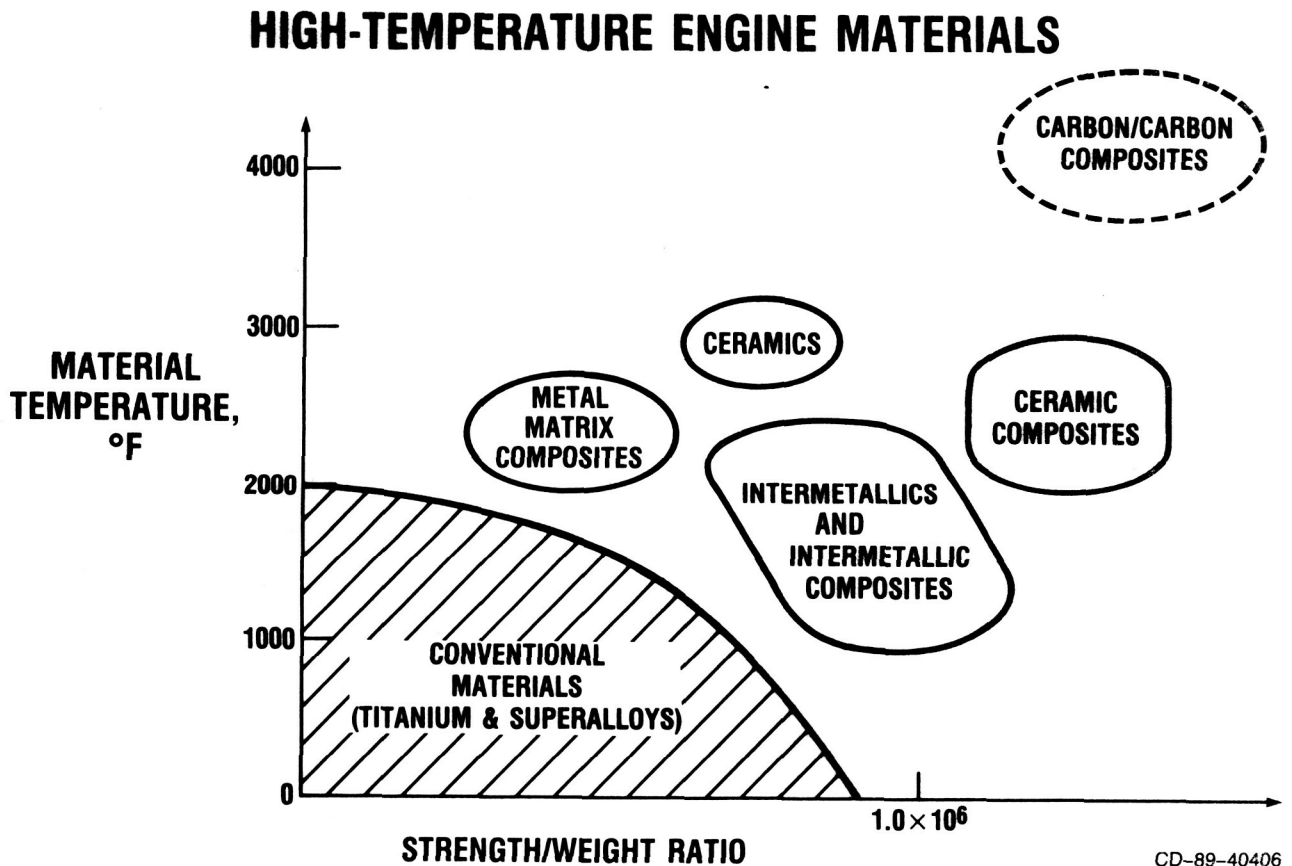
SUPERSONIC THROUGH-FLOW FAN ROTOR-STATOR INTERACTION STAGNATION ENTHALPY



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High-Temperature Composite Materials

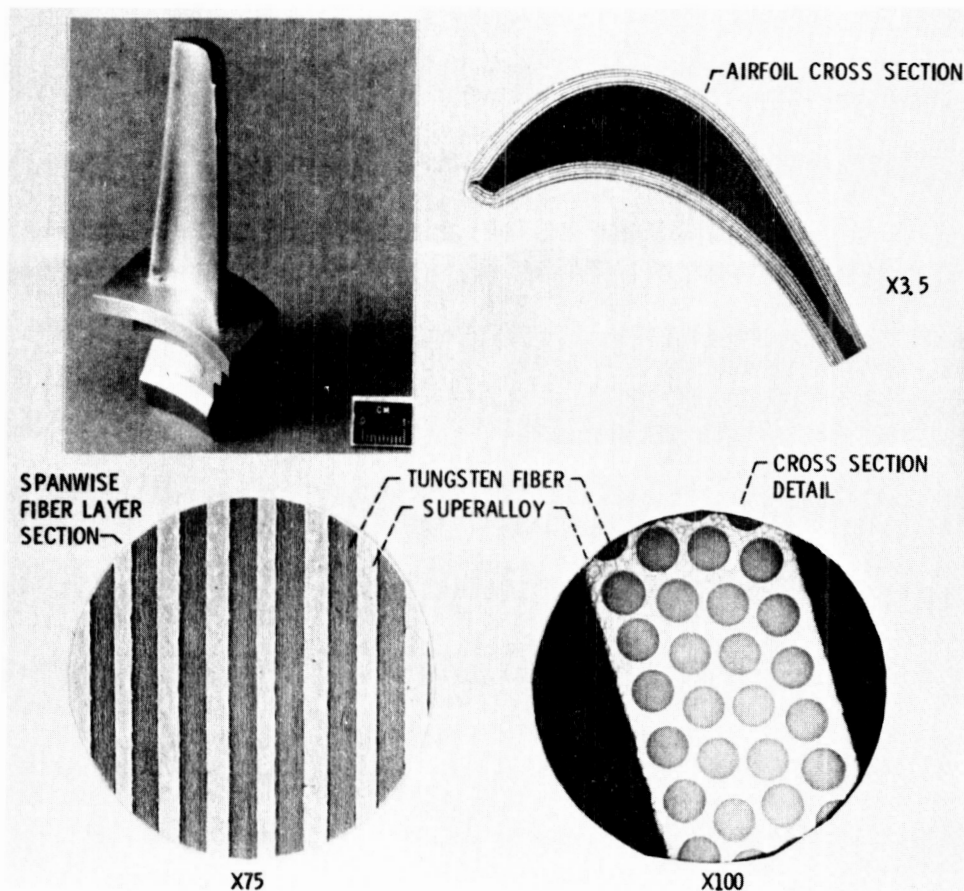
There are ever-increasing demands to develop low-density materials that maintain high strength and stiffness properties at elevated temperatures. Such materials are essential if the requirements for advanced aeropropulsion applications are to be realized. Metal matrix composites and intermetallic matrix composites are currently being investigated at NASA Lewis for such applications because they offer potential increases in strength, stiffness, and use temperature at a lower density than the most advanced single-crystal superalloys presently available. The enhanced strength/density ratio and increased operating temperature potential that metal matrix and intermetallic matrix composites offer over conventional materials are shown in this graph. Included also is the longer-term development of ceramics, ceramic composites, and carbon/carbon composites.



Superalloy Composite Blade

One highlight of past work performed at NASA Lewis is the fabrication of a tungsten-fiber-reinforced superalloy composite in the shape of a turbine blade. This proof of concept showed that production of intricately shaped composite components is indeed attainable. The composite blade was designed after a JT9D blade. It is hollow and contains cooling channels along the trailing edge. Note also that the fiber spacing in the longitudinal and transverse cross sections is uniform. The powder cloth method was employed in fabricating this blade.

TUNGSTEN-FIBER-REINFORCED SUPERALLOY COMPOSITE BLADE



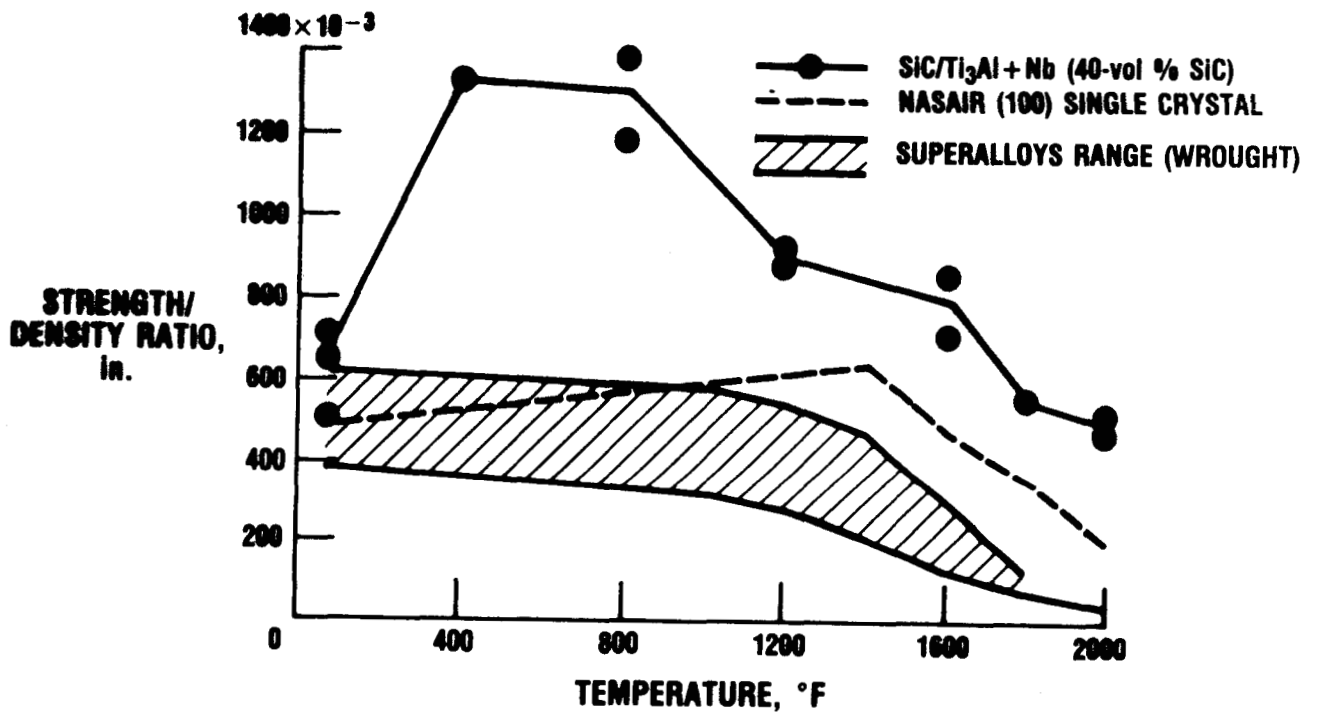
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Aluminide Matrix Intermetallic Composite

Current efforts in advanced materials for aeropropulsion applications include the development of continuously reinforced aluminide matrix composites because of the potential to outperform existing superalloys. One such intermetallic composite is SiC/Ti₃Al+Nb. Comparing measured SiC/Ti₃Al+Nb composite tensile properties on a strength/density ratio basis with those of a range of wrought superalloys and a single-crystal superalloy shows that the superior tensile properties predicted for aluminide matrix composites are attainable.

TENSILE PROPERTIES OF SiC/Ti₃Al + Nb COMPOSITE



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Brittle Materials Design Method

The life prediction focus at NASA Lewis is on understanding, predicting, and controlling structural failures. A wide range of advanced materials and material systems is being considered, many of them quite brittle and therefore unforgiving. The design of brittle ceramics differs from that of ductile metals because of the inability of ceramic materials to redistribute high local stresses caused by inherent flaws. Random flaw size and orientation require that a probabilistic analysis employing the weakest link theory be performed if the component reliability is to be determined.

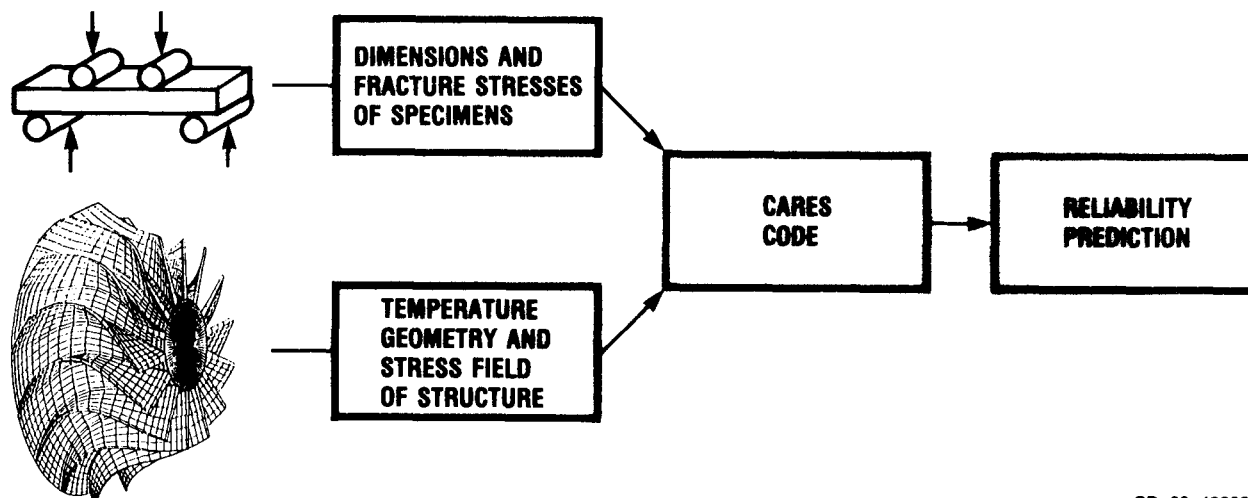
The lack of adequate design technology, such as general purpose design programs, standards, nondestructive evaluation (NDE) expertise, and codes of procedure prompted NASA Lewis to initiate research focused on ceramics for heat engines at the beginning of this decade. One of the early accomplishments of this effort has been the development of the unique, public-domain design program called Ceramics Analysis and Reliability Evaluation of Structures (CARES). This program is now in wide use for monolithic ceramics and is being extended to ceramic matrix composites.

CERAMICS/BRITTLE MATERIALS LIFE PREDICTION TECHNOLOGY

MATERIAL BRITTLINESS AND PRESENCE OF DEFECTS REQUIRE

- **PROBABILISTIC APPROACH ALLOWING FOR STRENGTH DISPERSION**
- **USE OF WEAKEST LINK THEORY TO TREAT SIZE EFFECT**
- **REFINED THERMAL AND STRESS ANALYSIS—FIELD SOLUTIONS**

RELIABILITY ANALYSIS CODE (CARES)

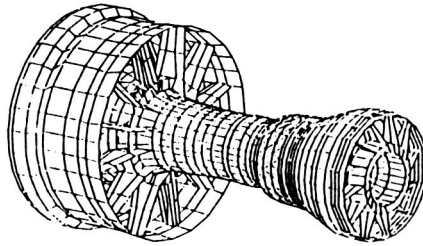


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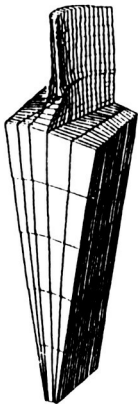
Engine Structures Computational Simulator

The Engine Structures Computational Simulator is intended to simulate the structural behavior/performance at test-stand and/or flight-mission conditions. The simulation can be for subcomponents, components (turbine blade), subassemblies (rotor sector), assemblies (rotor stage), and up to the entire engine. New design concepts, materials, mission requirements, etc., can be simulated and their potential benefits evaluated prior to detail design and testing initiation. Local or subcomponent damage effects on engine structural performance can be assessed and engine structural durability/integrity determined. With the availability of this information, the probability of unanticipated failures can be established and the safety of the engine structure ascertained. Current materials modeling capabilities for the Engine Structures Computational Simulator are primarily for metal systems. Models for metal matrix composites are beginning to become available while modeling for ceramic matrix composites has been initiated.

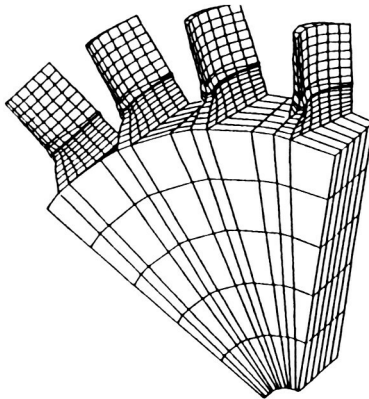
ENGINE STRUCTURES COMPUTATIONAL SIMULATOR



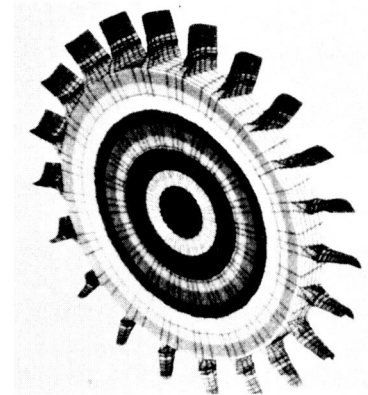
ENGINE FINITE ELEMENT MODEL



BLADE



ROTOR SECTOR



ROTOR STAGE

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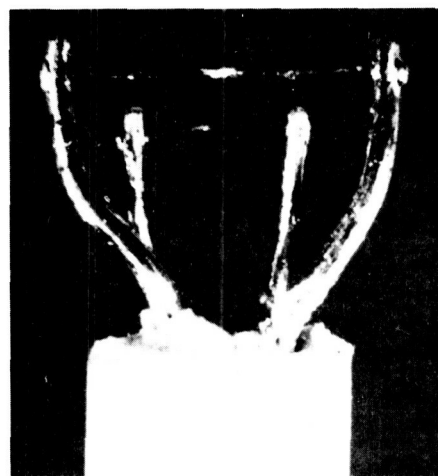
Dynamic Gas Temperature Measuring System

Current and future propulsion research will require instrumentation capability in ever increasingly hostile environments and usable in conjunction with advanced propulsion system materials such as ceramics and composites. In general, sensors are used in situ to either measure the environment at a given location within a turbine engine or to measure the response of an engine component to the imposed environment. Locations of concern are generally in the gas path and, for the most part, are within the hot section of the engine.

One of the most important environmental parameters in a turbine engine hot section is gas temperature. Normally only time-average temperature is measured. Fluctuations in gas temperatures are, however, of great concern for hot section durability and combustor modeling activities. In this measuring system, a probe with two wire thermocouples with different diameters provides dynamic data at frequencies up to 1000 Hz. When used at the turbine inlet of a PWA F-100 engine, this probe measured a peak-to-peak fluctuation of 900 °F. Such a large temperature fluctuation implies that there are filaments of primary combustion gas and dilution air in the combustor exhaust stream.

DYNAMIC GAS TEMPERATURE MEASURING SYSTEM

- **MEASURES GAS TEMPERATURE FLUCTUATIONS AT THE EXIT OF A TURBINE ENGINE COMBUSTOR**
- **A TWO-ELEMENT PROBE PROVIDES DATA TO PERMIT ACCURATE FREQUENCY COMPENSATION**



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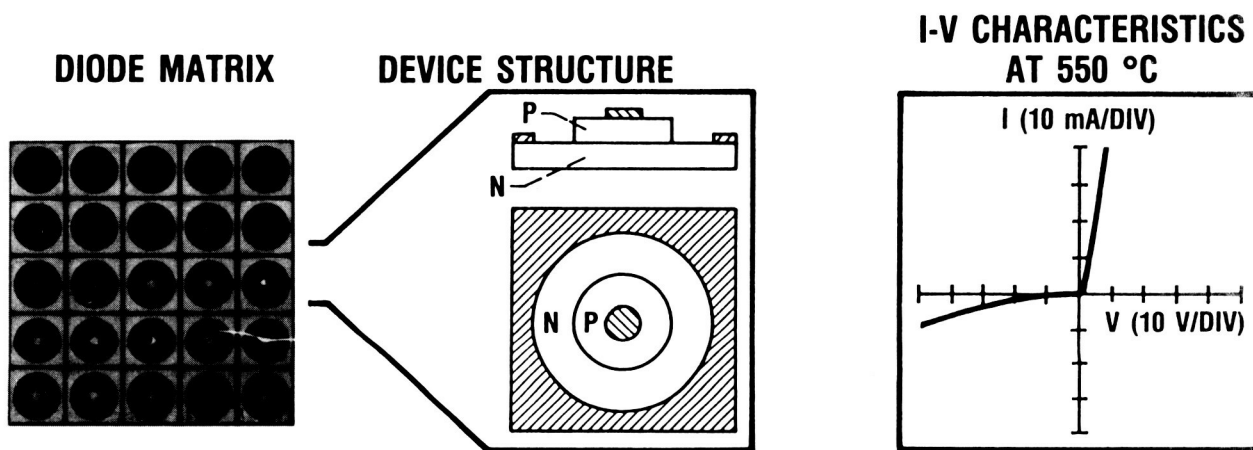
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Silicon Carbide Diode For High-Temperature Electronics

In recent years, there has been a growing need for electronics capable of sustained high-temperature operation for aerospace propulsion system instrumentation, control and condition monitoring, and integrated sensors. The desired operating temperature in some applications exceeds 600 °C, which is well beyond the capability of currently available silicon semiconductor devices. With the same criteria as applied to silicon, silicon carbide could theoretically be employed at temperatures as high as 1200 °C. A more reasonable, shorter term goal is to produce electronics capable of 600 °C operation. This material is characterized by excellent physical and chemical stability, which make it suitable for long-term use in high-temperature corrosive environments.

A Beta-SiC rectifying device, shown below, was fabricated at NASA Lewis using in-situ boron doping. Significantly improved operating characteristics, as compared to available devices, were obtained above 400 °C. The I-V characteristics at the maximum operating temperature of 550 °C are shown. Improved temperature capability for electronic devices will not only improve reliability, but will enable the electronics to be distributed to noncooled areas closer to the associated sensors and, thus, reduce system weight and complexity.

SILICON CARBIDE DIODE FOR HIGH-TEMPERATURE ELECTRONICS



BETA-SiC RECTIFYING DEVICE WITH OPERATIONAL CAPABILITY TO 550 °C AND SIGNIFICANTLY IMPROVED CHARACTERISTICS ABOVE 400 °C

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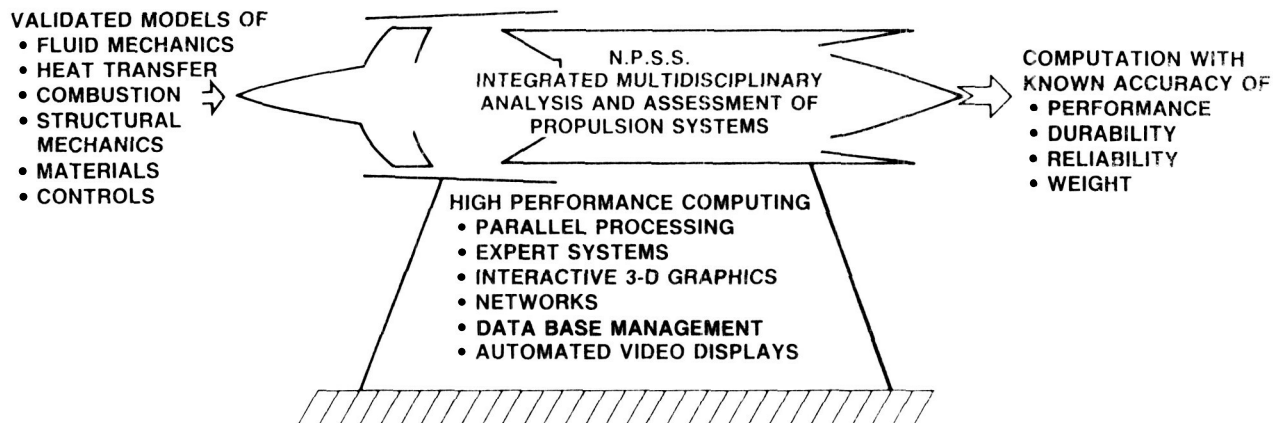
CONCLUDING REMARKS

A Numerical Test Cell

While NASA Lewis will continue to work on subsonic propulsion technology, the major part of our aeropropulsion program is shifting toward propulsion systems for flight at high speed. Meeting the performance goals while maintaining environmental compatibility will require revolutionary, rather than evolutionary, advances in propulsion capability through improved component aerodynamics, heat transfer, materials, and structures. A major consideration for any new propulsion system is the enormous time and cost, most of which can be attributed to the heavy dependence on hardware testing, to demonstrate performance and durability.

The recent history of propulsion has been marked by efforts to develop computational techniques that speed up the development process. To achieve significant reductions in the time and cost of propulsion system development will require major advances in propulsion system modeling, algorithm design, and computational technology. NASA Lewis has initiated an effort to develop, demonstrate, and validate new simulation hardware and software for multidisciplinary design, analysis, and optimization. To that end, we have begun to direct our computational fluid mechanics, computational structural mechanics, computational materials science, and high performance computing activities toward a common long-range goal for the development of technology for a numerical test cell.

A NUMERICAL TEST CELL



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| 16. Abstract This presentation highlights some of the recent contributions and future directions of NASA Lewis' research and technology efforts applicable to turbomachinery for high-speed flight. For a high-speed civil transport application, the potential benefits and cycle requirements for advanced variable cycle engines and the supersonic throughflow fan engine are presented. The supersonic throughflow fan technology program is discussed. Technology efforts in the basic discipline areas addressing the severe operating conditions associated with high-speed flight turbomachinery are reviewed. Included are examples of work in internal fluid mechanics, high-temperature materials, structural analysis, instrumentation and controls. | | | | | |
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